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Forest Ecology and Management 87 (1996) 27–39

Forest Ecology and Management

Expanding the scale of forest management: allocating timber harvests in time and space

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Accepted 26 April 1996

Abstract

This study examined the effect of clustering timber harvest zones and of changing the land use categories of zones (dynamic zoning) over varying temporal and spatial scales. Focusing on the Hoosier National Forest (HNF) in Indiana, USA as a study area, I used a timber harvest allocation model to simulate four management alternatives. In the static zoning alternative, harvests were dispersed throughout the timber harvest land base (65% of HNF) for 15 decades. The three dynamic zoning alternatives varied in the degree to which harvests were clustered in time and space. Two levels of harvest intensity were simulated, and at each level of harvest intensity, the area harvested was held constant among all four zoning alternatives. The dynamic zoning strategies resulted in substantial increases in the amount of forest interior and reductions in the amount of forest edge across the landscape, as well as an increase in the average age of stands when harvested. The greatest reduction in fragmentation was produced by the alternative that most tightly clustered harvests in time and space (i.e. intensive harvesting of small blocks in a relatively short time). When harvest intensity was high, this alternative produced amounts of forest interior and edge comparable to those of the dispersed alternative with half the rate of harvest. The results suggest that the injection of dynamics in specifying disturbance regimes, and the clustering of disturbance in time and space, can be used to sustain larger blocks of mature forest than can static zoning. Dynamic zoning encourages explicit specification of the disturbance regimes that will be imposed across the land base over long periods of time.

Keywords: Forest management planning; Fragmentation; Disturbance; Forest interior; Forest edge; Multiple use; Temporal scale; Clustering timber harvests; Simulation modeling

1. Introduction

Forest management has become controversial, stemming from fundamental differences in how forest resources are viewed by different segments of society. The management of federally owned forests is mandated by law to provide for multiple uses and values through the National Forest Management Act of 1976. Industrial forest owners have also made a commitment to provide multiple forest values in the management of their forest lands (Wallinger, 1995). Forest management plans typically allocate the land base among several land use categories, and projections are made of the impacts of the plans on a suite of forest values, including biological diversity, recreational opportunities, and commodity production.

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PII S0378-1127(96)03838-8

Because of this goal to provide for multiple uses, planners often find themselves attempting to provide for mutually exclusive uses of land, such as timber production and old-growth forest. A typical model is to designate several land use categories, and to allocate land to these categories, thus grouping suites of compatible land uses into spatially defined zones. Examples of objectives associated with various land use categories might be 'a physical setting to provide opportunity for solitude and a feeling of closeness to nature'; or 'provide for recreation facilities'; or 'maintain habitat diversity, provide a sustained yield of timber, and provide dispersed recreation opportunities.' Usually several blocks of land (management areas) are allocated to each land use category, and these blocks are dispersed throughout the forest, ostensibly to provide the values associated with each category across the landscape. This approach provides for multiple uses at the landscape scale, but may not adequately integrate multiple uses within each management area (Behan, 1990). For example, timber production has increasingly been viewed as being incompatible with many non-commodity uses of the forest, and is often segregated from those uses.

Forest plans typically consider a 50-year planning horizon. In many cases, it is not possible to provide all potential uses within a management area over a 50-year period. However, interesting possibilities arise when considering longer temporal scales. Should the designation of the land use(s) within a management area be static for long periods of time (static zoning), or should it be dynamic, with several land uses rotating among several management areas (dynamic zoning) at a scale of centuries? For example, timber production might be allowed periodically in a non-timber production area to prevent native oak–hickory forests from succeeding to beech–maple. On the other hand, timber production areas could be allowed to lay fallow to provide non-commodity values for some period of time. The current management paradigm appears to allow for spatial and temporal management dynamics within a management area, but little thought has yet been given to dynamics in the designation of management areas over long time periods (over 50 years). The interaction of the spatial and temporal domains of management activity has been inadequately explored, but has significant consequences for the ecological conditions of managed forests (Crow and Gustafson, 1996).

A poorly understood consequence of static zoning is that forest age class distributions become skewed over long time periods (Gustafson and Crow, 1996). Stands in timber production areas are kept in relatively early seral stages; other management areas experience little disturbance, and the forest in those areas will eventually be dominated by late-seral types. Intermediate seral stages should become rare as a consequence of the deterministic disturbance regime imposed by static management strategies over long periods of time, and community composition may change markedly. Deterministic disturbance regimes may reduce the natural variability of landscapes, resulting in undesired ecological conditions (Mladenoff and Pastor, 1993; Swanson et al., 1994; McCarthy and Burgman, 1995).

A recent trend in US National Forest management has been a reduction of more than 50% in timber production since 1988, to the lowest levels since about 1955 (Haynes et al., 1995). This trend has primarily been in response to pressure to provide for more non-commodity values from National Forests, such as wildlife habitat and a natural setting in which to experience nature. As an example of this, the Hoosier National Forest in southern Indiana amended its 1985 Forest Plan, which emphasized clearcutting on 85% of the land base (USDA Forest Service, 1985), changing the management emphasis to uneven-age management. This amendment reduced the expected timber output by 60% and set aside 60% of the land base for non-commodity purposes (USDA Forest Service, 1991).

It remains to be seen if a policy of sharply curtailed commodity production will be socially acceptable in the long term. Virtually every member of society uses wood-based products, and the demand for wood is projected to rise more than 60% by the year 2040 (Haynes et al., 1995). Forest products are renewable, unlike many substitutes. Reduced timber production on federal lands increases demand for private and foreign timber. Industrial forest owners also experience pressure to provide non-commodity values from their forests. Forest planners have the unenviable task of attempting to balance the conflicting demands by society for commodity and non-commodity values from forested lands. The challenge will be to develop new management paradigms that allow commodity production while maintaining non-commodity values.

One of the potential ecological consequences of timber harvest is a reduction in the amount of habitat for forest interior species, many of which are thought to be declining in abundance (Robbins et al., 1989; Hill and Hagen, 1991). Most harvest methods create openings that perforate blocks of contiguous forest and introduce edge habitat within the forest. Many interior species are thought to be sensitive to the size of forested blocks (Blake and Karr, 1987; Freemark and Collins, 1992), and internal edges may provide improved habitat for generalist predators and brood parasites (Gates and Gysel, 1978; Brittingham and Temple, 1983; Small and Hunter, 1988; Robinson et al., 1995).

The practice of dispersing cutting units has been implicated as a major contributor to the reduction in forest interior habitat and the increase in linear edge (Franklin and Forman, 1987; Gustafson and Crow, 1994; Wallin et al., 1994). Progressive cutting across the landscape has been proposed as an alternative to the traditional approach of dispersing cutting units across the landscape (Li et al., 1993). Under this strategy, timber harvesting would proceed somewhat systematically across the landscape. Openings produced by harvest would be clustered in both time and space, allowing more interior habitat to be sustained on the landscape as a whole. The practical application of this approach is complicated by discontinuous ownership of the landscape and the variability in the suitability of stands for harvest at any given point in time. A variant of this approach might be to progressively designate timber harvest management areas across the landscape over successive planning periods (dynamic zoning). This would also have the effect of clustering harvest openings within the larger landscape, but would allow more flexibility in the placement of individual harvest treatments within the management area. Flexibility at the watershed scale is essential to mitigate the effects of cutting on stream flow and sediment production (Hornbeck and Swank, 1992) and to protect special resource features and habitats (Naiman et al., 1993). Spatial clustering of harvests by progressive cutting also has implications for disturbance (by harvest) return intervals. When harvests are highly aggregated, the disturbance occurs in a relatively small area over a short time period, and a relatively long period free from harvest disturbance follows. Thus, dynamic zoning produces a clustering of harvest disturbance in both space and time. Dynamic zoning is a potential tool to produce dynamic landscape heterogeneity (Mladenoff and Pastor, 1993) by implementing harvesting cycles, and encouraging explicit specification of disturbance regimes over large spatial and temporal scales.

In this study, I used a timber harvest allocation model to compare four cutting strategies that differed in the spatial and temporal dispersion of harvest allocations. My objective was to quantify the changes in forest interior habitat and forest edge produced by different harvest dispersion strategies, providing insight into the utility of dynamic zoning strategies for forest management. Recent studies have demonstrated the value of clustering harvests spatially through time (Li et al., 1993; Gustafson and Crow, 1994; Wallin et al., 1994), but here I also examine the effect of dynamically changing the locations of timber harvest zones.

2. Methods

2.1. Study area

The study was conducted on a rectangular study area (1 058 046 ha) that included the entire Hoosier National Forest (HNF) Purchase Area, located in southern Indiana, USA (Fig. 1). The HNF was used to provide realistic ownership and Management Area (MA) patterns for assessing alternative cutting strategies. The HNF is typical of National Forests in the eastern USA in that the ownership pattern is highly fragmented by privately-owned inholdings, and the HNF owns only about 43% of the land within the Purchase Area. In published Forest Plans, MA boundaries have been drawn that specify the management direction for the federally owned land within each MA. I defined the land base on which timber harvest was to be simulated using the MA boundaries of the 1991 HNF Amended Plan (USDA Forest Service, 1991). Ownership boundaries were digitized from 1:24000 scale paper maps produced by the US Geological Survey (USGS) for the Forest Service

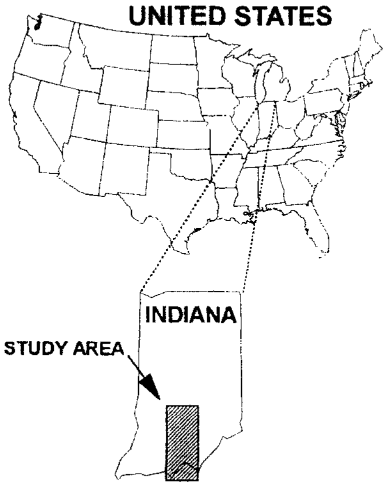

Fig. 1. Location of study area.

(Fig. 2(a)). MA boundaries were manually transferred from the Forest Plan maps (approximate scale, 1:127000) to 1:100000 scale USGS maps and digitized. A forest cover map of the entire Purchase Area was generated from USGS-Land Use Data Acquisition (LUDA) data, and all layers were gridded to a common cell size of 100 by 100 meters. It was not feasible to digitize stand age maps of the entire HNF and stand age data were not available for private land, so I assumed that the distribution of past harvest activity (and therefore stand ages) is spatially random on the HNF. I tested the assumption that stands reaching rotation age and past harvest allocations are randomly distributed using nearest-neighbor analysis (Davis, 1986) on ten subsets of HNF stand maps (mean ($\pm$SD) size of subsets 3366 $\pm$ 1062 ha). The observed mean nearest-neighbor distance between stands of similar age was compared with the distance expected if stands were randomly distributed, and a z-statistic was computed. The null hypothesis that stands are randomly distributed could not be rejected at the 95% confidence level for eight of the ten subsets (see Gustafson and Crow, 1996).

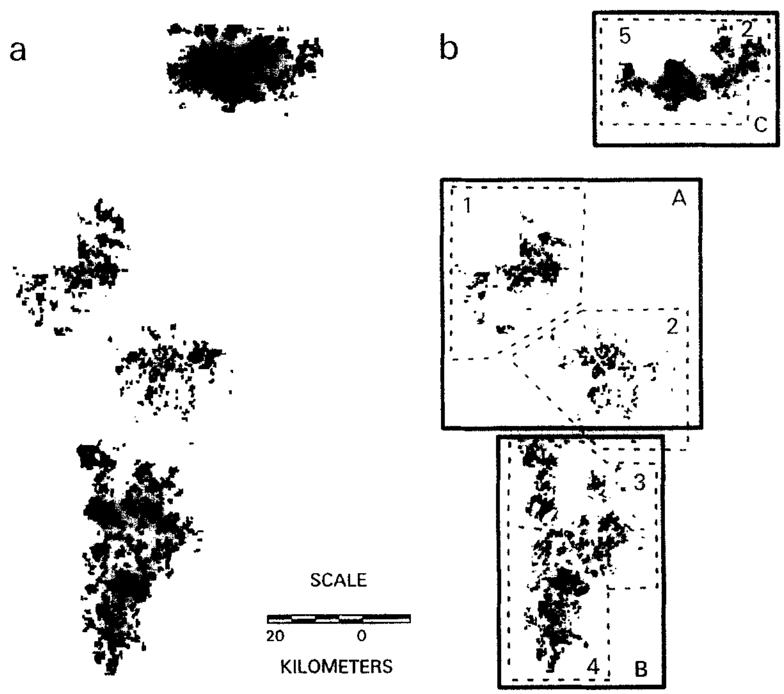

Fig. 2. Map of (a) distribution of land owned by the HNF within the study area and (b) timber land base on which harvests were simulated. The solid-line rectangles represent the subsets used for the 50-year and 100-year hiatus alternatives, and the dashed lines represent the subsets used for the 120-year hiatus alternative. Upper case letters indicate the order in which timber harvest was allowed on the subsets for the 50- and 100-year hiatus alternatives, and the numbers indicate the order in which timber harvest was allowed on the subsets for the 120-year hiatus alternative.

2.2. Timber harvest allocation model

HARVEST is a timber harvest allocation model that was constructed to allow the input of specific rules to allocate forest stands for even-age harvest (clearcuts and shelterwood) and group selection, using parameters commonly found in National Forest Plan standards and guidelines. The model produces landscape patterns that have spatial attributes resulting from the initial landscape conditions and the proposed management activities. The model is simplistic in that it does not attempt to optimize timber production or quality, nor does it predict the specific locations of future harvest activity, as it ignores many considerations such as visual objectives and road access. Instead, the model stochastically mimics the allocation of stands for harvest by forest planners, using only the constraints of the standards and guidelines and MA boundaries. Modeling this process allows experimentation to link variation in management strategies with the resulting pattern of forest openings.

HARVEST was constructed to be used in conjunction with a grid-cell Geographic Information System (GIS), with routines for direct input and output of ERDAS v. 7.5 GIS files, but supporting files exported in text format from other raster GIS systems. Timber harvest allocations were made by the model using a digital stand map, where grid-cell values reflect the age (in years) of the forest in that cell. HARVEST takes a GIS stand age map as input, and produces a new stand age map incorporating harvest allocations. HARVEST allows control of the size distribution of harvests, the total area of forest to be harvested, and the rotation length (by specifying the minimum age on the input stand map where harvests may be allocated). HARVEST selects harvest locations randomly within currently active timber production MAs, checking first to ensure that the forest is old enough to meet rotation length requirements. This is consistent with the random distribution of past harvest activity, as discussed above. Since the initial forest ages were unknown, but assumed to be spatially random, I allowed the model to choose harvest locations randomly from all cells within timber production areas by assigning all forest an initial age of 100 years. This assumed that sufficient area of forest old enough to be harvested existed in timber production areas during the initial decades of simulation to meet target harvest levels. A consequence of this procedure was that the distribution of stands less than 20 years of age (openings) in the first two decades of simulation was not explicitly modeled, so the initial forest condition appeared less fragmented than is probably the case.

2.3. Experimental design

The land base harvested over a period of 15 decades was determined by the Management Area boundaries specified in the 1991 HNF Amended Plan (USDA Forest Service, 1991). In the 1991 Amended Plan, timber harvest was allowed on 39 299 ha, but for the alternatives simulated in this study I also allowed timber harvest on an additional 9585 ha, to allow for higher timber outputs than projected under the 1991 Amended Plan. Timber production was allowed on approximately 65% of the HNF land base, and only on land owned by the HNF (Fig. 2(b)).

The experimental treatments consisted of alternative designations of timber harvesting areas on the HNF that varied as to where timber harvest was allowed during each decade and for how many decades it was allowed there. The total land base that was harvested (timber harvest land base) over a period of 15 decades was identical among all alternatives. For the static zoning alternative, harvest was allowed throughout the timber harvest land base during all 15 decades. Three dynamic zoning alternatives were simulated. For the '50-year hiatus' alternative, the timber land base was divided into three subsets; timber harvest was allowed on only two of these subsets at a time (beginning with subsets A and B, Fig. 2(b)), and the third was temporarily set aside from timber harvest for 50 years. The treatments were rotated every 5 decades, so that each subset was harvested for 10 successive decades and then set aside from timber harvest for 5 decades. For the '100-year hiatus' alternative, the same three subsets were used, but timber harvest was allowed on only one of these subsets at a time (beginning with subset A, Fig. 2(b)), and the other two were temporarily set aside from timber harvest. Again, the treatments were rotated every 5 decades, and each subset was harvested for 5 successive decades and then set aside for 10 decades. Finally, for the '120-year hiatus' alternative, the timber harvest land base was divided into five subsets, and each subset was harvested for 3 decades (beginning with subset 1, Fig. 2(b)) and then was set aside for 12 decades. Total area harvested, size of harvest openings, and rotation interval (minimum age for cells to be harvested) were held constant across all treatments and decades, so that timber production was the same for all four scenarios.

Timber harvest parameters were chosen to fall within the parameter space of the 1985 Plan and 1991 Amended Plan alternatives simulated elsewhere (Gustafson and Crow, 1996) and are detailed in Table 1. Only harvest methods that produce forest openings (clearcut, shelterwood and seedtree) were simulated, and harvest placement was not constrained by adjacency prohibitions. The intensity of harvest (total area harvested) is an important determinant of forest interior and edge (Gustafson and Crow, 1994), so I conducted simulations at two levels of harvest intensity, one having twice as much area harvested each decade as the other. This allowed me to assess the relative contribution of both dispersion of harvests and intensity of harvest to the amount of forest interior and edge. Higher levels of sustained harvest were not possible without increasing the timber land base. Thus, a complete factorial design was implemented, with four levels of cutting pattern (static, 50-year hiatus, 100-year hiatus, and 120-year hiatus), and two levels of harvest intensity (1300 ha per decade and 2600 ha per decade). Three replicates of each factorial combination were produced.

2.4. Analysis

At each decade, I used a GIS to determine the amount of forest interior habitat (forest over 300 m from an opening or edge). A simple FORTRAN routine was written to calculate linear forest edge. Clearcut stands in the HNF generally achieve canopy closure in 12–20 years (T. Thake, personal communication, 1993), so cells harvested were assumed to create openings in the forest for 20 years and were then assumed to return to a closed canopy condition. A different definition of canopy closure would change the absolute amount of interior and edge, but the relative differences among alternatives would be similar to those reported here. The total amount of edge and interior was plotted over simulated time for each of the alternative cutting patterns. For comparison, the results of simulating the original 1985 Forest Plan and the 1991 Amended Plan (Gustafson and Crow, 1996) were also plotted.

To evaluate the relative effects of harvest dispersion and harvest intensity on forest interior and edge,

Table 1
Harvest intensities used in the simulation of timber harvest alternatives on the Hoosier National Forest. The High and Low Intensity parameters were used for the simulation of the static and dynamic zoning cutting alternatives. Analysis included three replicates of simulations conducted for 15 decades

Model parameter	Low Intensity	High Intensity	1985 Plan	1991 Plan
Mean clearcut opening size (ha)	5.0	5.0	4.0–7.0	2.8
Mean group opening size (ha)	NA	NA	0.4	0.2
Maximum opening size (ha)	8.0	8.0	10.8	4.0
Total harvested per decade [a] (ha)	1300.0	2600.0	5709.6	1267.0
Harvest rate per decade [b] (%)	2.6	5.3	10.5	3.2
Rotation length (years)	100	100	80–120	80
Timber land base (ha) [c]	48884	48884	56279	39299

[a] Represents harvest activity across the entire forest. Total HNF ownership is approximately 84774 ha.
[b] Represents the percentage of forest within the timber harvest land base that is harvested each decade.
[c] Total area where harvest is allowed during at least part of the 15-decade simulations.

an ANOVA was used to test for treatment effects reflecting harvest dispersion (DISPERSION), harvest intensity (INTENSITY), and time (DECADE). The time periods were included in the analysis to account for the potential correlation of measures of forest interior and edge in successive decades.

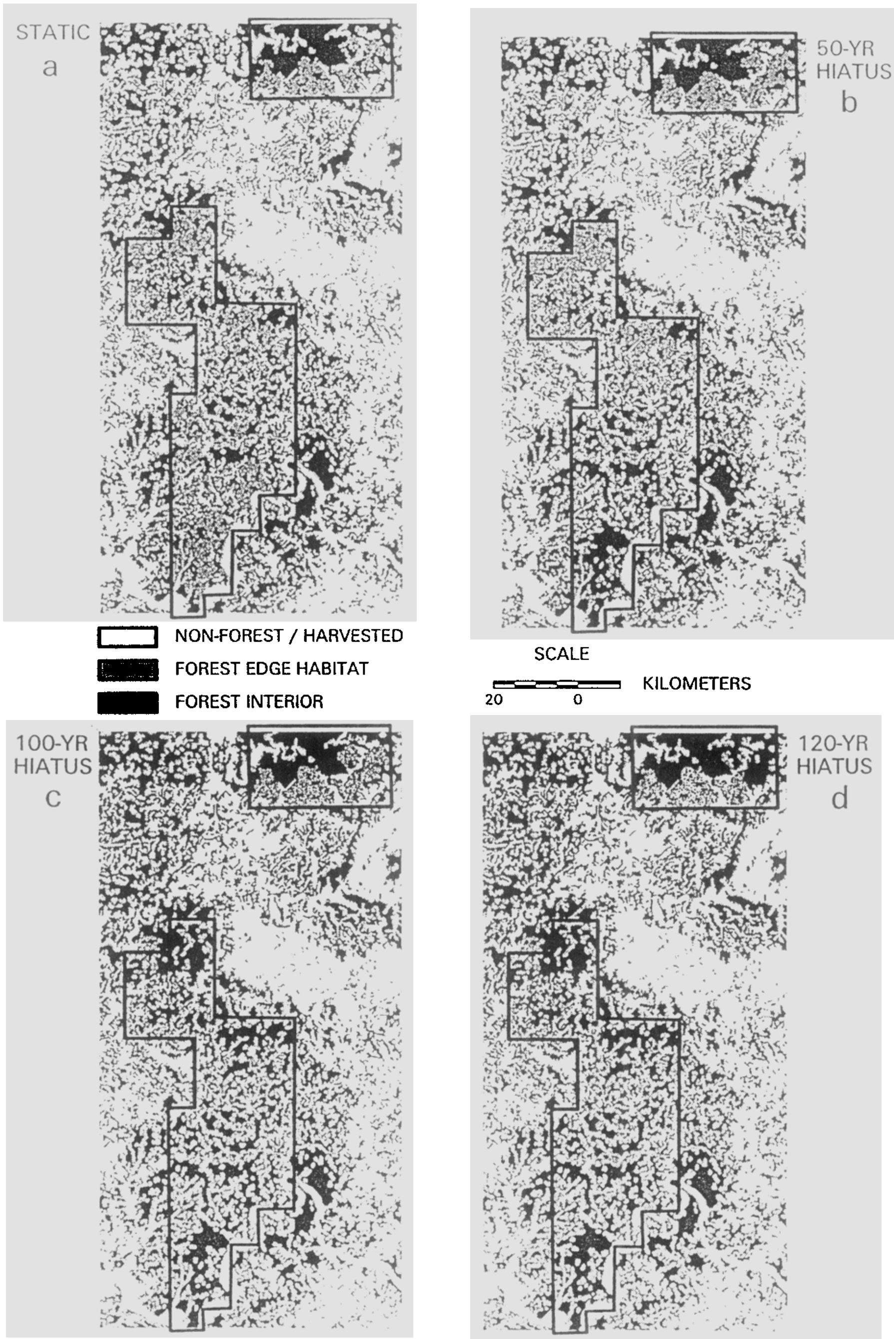

Fig. 3. Forest interior in the study area at the end of 15 decades of simulated harvest at the 'High intensity' harvest rate (2600 ha per decade) under the four zoning alternatives. The solid lines represent the approximate location of the HNF Purchase Boundary, and simulated harvests occurred only on HNF land within those boundaries.

3. Results

The total amount of forest interior varied markedly among the simulated alternatives (Fig. 3), with the highest amount produced by the pattern that most tightly clustered harvests in time (i.e. longest hiatus period) and space (120-year hiatus, Fig. 3(d)). Under the static alternative, none of the timber land base was set aside at any time; large amounts of forest edge habitat can be seen scattered throughout the HNF Purchase Area, and few blocks of forest interior remain (Fig. 3(a)). Under the dynamic zoning alternatives, increased amounts of forest interior can be seen in the areas that had just completed their fallow period; for example, examine subset B (Fig. 2(b), Fig. 3(b)) and subsets A and B (Fig. 2(b), Fig. 3(c)), representing the 50-year and 100-year hiatus alternatives, respectively. Forest interior reaches its highest levels on the landscape as a whole under the 120-year hiatus alternative (Fig. 2(b), Fig. 3(d)). Timber production is evident in subset 5 under this alternative, where the density of harvest openings is quite high, due to the high level of clustering.

The replications of the simulations produced little variability in forest interior and edge. The variability was too low to show clearly with error bars on line graphs, so error bars are not shown. The standard deviation from the mean of interior area produced by three replicates never exceeded 0.5% in any combination of treatments, and the standard deviation from the mean linear edge never exceeded 0.02%.

The dynamic zoning strategies resulted in more forest interior across the landscape than the static zoning alternative (Fig. 3), with the highest amount produced by the pattern that most tightly clustered harvests in time and space (120-year hiatus, Fig. 3(d), Fig. 4). The dynamic zoning strategies also resulted in less forest edge across the landscape than the static zoning alternative, with the least amount again produced by the pattern that most tightly clustered harvests in time and space (120-year hiatus, Fig. 5).

The periodic rise and fall in the amount of forest interior and forest edge evident in the dynamic zoning alternatives was caused by the initiation of cutting on a new cutting zone. Openings were produced in the new zone before all the openings closed on the previous zone, so that for a 2-decade period harvest

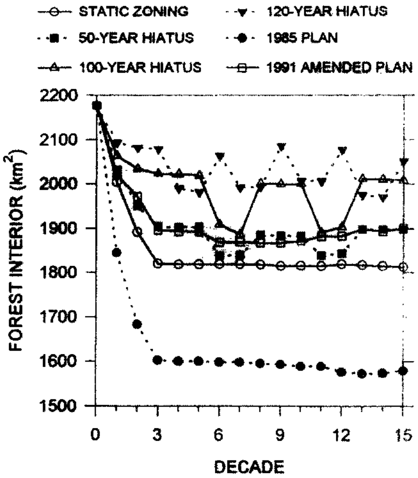

Fig. 4. The amount of forest interior produced by timber harvest alternatives over simulated time on the Hoosier National Forest (HNF). The 'Static' alternative is the least clustered in space and time, while the '120-year hiatus' alternative is the most clustered in space and time. The results plotted are for the 'High intensity' harvest rate (2600 ha per decade). The 1985 Plan and 1991 Amended Plan are simulations of published plans for the HNF (Gustafson and Crow, 1996), and are shown for comparison.

openings existed on two zones, perforating contiguous forest habitat across a broader portion of the landscape. One might expect that forest edge would not show such a pattern, since edge is introduced around an opening, regardless of the spatial dispersion of the openings. However, when harvest intensity was high, openings (cells less than 20 years old) within the timber production zones begin to coalesce, reducing edge. The oscillation in the amount of edge seen in Fig. 5 reflects this periodic coalescence of openings near the end of production in a zone, and generation of relatively higher amounts of edge when new cutting zones were opened. This oscillation is not evident at low harvest intensity (not shown).

Levels of fragmentation under a dynamic zoning alternative with a high intensity of harvest were comparable with those produced by the static alternative with a low level of harvest (Fig. 6). Note in Fig. 4 that even the 50-year hiatus alternative (high intensity is plotted) produced approximately the same amount of forest interior as the 1991 Amended Plan, even though the total area harvested under the 50-year hiatus alternative was twice that of the 1991 Amended Plan (Table 1). With a cutting intensity similar to

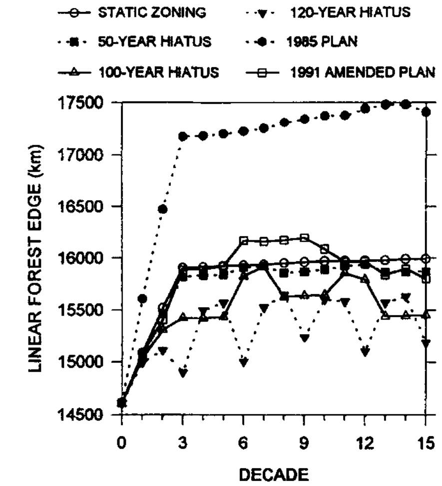

Fig. 5. Amount of forest edge produced by timber harvest alternatives over simulated time on the Hoosier National Forest (HNF). The 'Static' alternative is the least clustered in space and time, while the '120-year hiatus' alternative is the most clustered in space and time. The results plotted are for the 'High intensity' harvest rate (2600 ha per decade). The 1985 Plan and 1991 Amended Plan are simulations of published Plans for the HNF (Gustafson and Crow, 1996), and are shown for comparison.

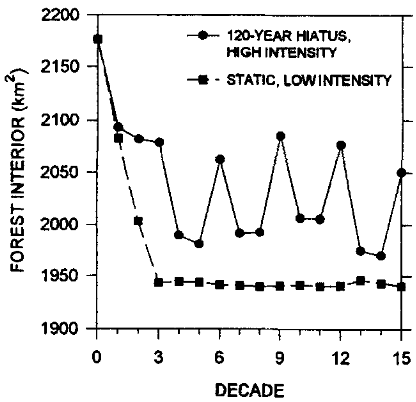

Fig. 6. Amount of forest interior produced over simulated time by the '120-year hiatus' alternative at high-intensity harvest (2600 ha per decade) and the 'Static' alternative at low-intensity harvest (1300 ha per decade). The 'Static' alternative is the least clustered in space and time, while the '120-year hiatus' alternative is the most clustered in space and time.

that of the 1991 Plan (low intensity), all the alternatives, including the static one, produced more forest interior than the 1991 Plan (plot not shown). This was due to the use of smaller openings in the 1991 Plan, including extensive use of group selection, which resulted in more openings that perforated the forest. The 1991 Plan, with an intensity of harvest approximately half that of the high-intensity dynamic zoning alternatives, produced higher amounts of edge due to the use of group selection.

Differences in the spatial dispersion of harvests (zoning) appear to have a greater effect on the amount of forest interior than do differences in harvest intensity. All the main effects are highly significant in the ANOVA models; however, examination of the sums of squares shows that the spatial dispersion of harvests (DISPERSION) explains 49.6% of

Table 2
Analysis of variance comparing the effects of harvest intensity (INTENSITY), the spatial dispersion of harvest activity (DISPERSION), and the time period simulated (DECADE) on the area of forest interior and linear forest edge maintained on the landscape. Analysis included three replicates of simulations conducted for 15 decades

Source	d.f.	Forest interior (km^2)				Forest edge (km)			
		SS	*F*	Prob > *F*	R^2	*SS*	*F*	Prob > *F*	R^2
INTENSITY	1	427298	402.6	0.0001		16178271	861.2	0.0001	
DISPERSION	3	1190387	373.8	0.0001		5792713	102.8	0.0001	
S v 50 [a]	1	78501	74.0	0.0001		95386	5.1	0.0249	
50 v 100 [b]	1	219118	206.4	0.0001		1000327	53.2	0.0001	
100 v 120 [c]	1	56061	52.8	0.0001		717132	38.2	0.0001	
S&50 v 100&120 [d]	1	1055825	994.7	0.0001		4980195	265.1	0.0001	
DECADE	14	421361	28.4	0.0001		8604716	32.7	0.0001	
Error	341	361959				6406158			
Total	359	2401006			0.85	36981858			0.83

[a] Orthogonal contrast of the Static (S) zoning alternative with the 50-year (50) hiatus alternative.
[b] Orthogonal contrast of the 50-year (50) hiatus alternative with the 100-year (100) hiatus alternative.
[c] Orthogonal contrast of the 100-year (100) hiatus alternative with 120-year (120) hiatus alternative.
[d] Orthogonal contrast of the Static (S) and 50-year (50) hiatus alternatives with the 100-year (100) and 120-year (120) hiatus alternatives.

the total variance of forest interior, while harvest intensity (INTENSITY) explains 17.8% of the variance and DECADE explains 17.5% (Table 2). Orthogonal contrasts partitioning the variation caused by DISPERSION (Table 2) show that the greatest variance is explained by differences between the 50-year and the 100-year hiatus alternatives (9.1%), and that the variance explained by differences between the two least aggregated alternatives (static and 50-year hiatus) and the two most aggregated alternatives (100-year and 120-year hiatus) is 44.0%.

INTENSITY is more important in explaining the length of forest edge, explaining 43.7% of the total variance, while DISPERSION explains only 15.7% of the variance and DECADE explains 23.3% (Table 2). With a given harvest size, each opening produces a fixed amount of edge, and the number of openings produced is proportional to harvest intensity. The spatial dispersion of openings has some impact on edge, in that more aggregated harvests tend to produce a coalescence of openings that reduces the relative amount of edge produced. Orthogonal contrasts partitioning the variation in edge caused by DISPERSION show trends similar to those of forest interior, but at lower levels of variance explained (Table 2).

Clustered harvests with longer hiatus periods resulted in an increase in the average age of stands in timber production zones on subsequent re-entries. The average age of forest cells at the end of 15 decades under the static alternative was 110.2 years. The average age of cells in a zone after its hiatus period was 118.0 years under the 50-year hiatus alternative, 146.2 years under the 100-year hiatus alternative, and 163.3 years under the 120-year hiatus alternative. The dynamic zoning alternatives had the effect of aggregating older forest stands by clustering disturbance.

4. Discussion

These results demonstrate the potential benefits of enlarging the spatial and temporal scale of forest management planning and of incorporating long-term temporal dynamics (dynamic zoning) into management plans. I found differences in forest fragmentation that resulted not from the amount of timber produced, but from the temporal and spatial configuration of its extraction. Specifically, as harvests became more aggregated in time (longer hiatus interval) and space, the level of fragmentation decreased, the average age of forests in timber management zones increased, and the disturbance interval necessary to achieve a given level of harvest was lengthened. Relative to static zoning, dynamic zoning increases opportunities to reduce the amount of edge and increase both the amount of interior habitat and timber production by clustering harvest activity and lengthening disturbance intervals. Although I simulated specific hiatus intervals, the important point is not the length of these intervals, but the temporal and spatial dynamics of the clustering that coincidentally produced these intervals. These results were obtained by simulating dynamic zoning on a National Forest, but the principle of clustering harvests in both time and space can be applied to the management of any large land base. Industrial forests are managed to maximize mean annual increment of timber volume and to favor the regeneration of certain tree species. Clustering disturbance by dynamic zoning with a rotation interval < 100 years would produce less fragmentation than dispersing disturbance with a similar interval. Dynamic zoning can also serve to cluster operational activities such as road improvement, access control, and site preparation, lowering costs of production.

The simulations reported here did not include the effects of any disturbance other than timber harvesting. Such effects may be significant on some landscapes, but are probably minimal on the HNF. On the HNF, prescribed fire has been used to maintain barrens and oak–hickory communities, but wildfire is rare and localized in this moist Central Hardwood region. Windthrow is more common, but its effects are also generally local. Natural disturbance in this region would produce some fine-grained, local patchiness, but its overall impact on landscape pattern would likely be minimal on a landscape of this size, even over a period of 15 decades.

Consideration of the temporal and spatial scale of disturbance is critical for the understanding of ecological processes (Urban et al., 1987; Wiens, 1989; Reice, 1994). The designation of MAs on managed forests essentially specifies the disturbance regime for each area of the forest. Timber harvest imposes periodic disturbance that changes the community at a spatial scale of several hectares, and the intensity of harvest is a major determinant of the resulting community structure and composition. In other MAs, disturbance may be suppressed, with very little management that might directly change community composition or landscape pattern. Thus, static zoning causes specific disturbance regimes to exist in perpetuity in specific locations. It is not clear what the impacts of static zoning on biotic diversity might be over long time periods. It has long been accepted that disturbance produces the spatial heterogeneity that is necessary to maintain diversity. However, the long-term role of disturbance is sometimes minimized in the management of 'natural ecosystems' (Attiwill, 1994). Non-equilibrium theories of community structure suggest that the diversity of species and the coexistence of similar species that is seen in most communities are due to some level of disturbance and the resulting opportunity for recruitment of new species to the community (Connell, 1978; Huston, 1979; Lewin, 1986; Reice, 1994). How ecosystems will respond to novel disturbance regimes is not often understood (Swanson et al., 1994). For example, in the Central Hardwood region, there appears to be a trend toward the conversion of native oak–hickory communities to beech–maple, thought to be the result of fire suppression (Lorimer, 1985). It is far from clear how the rest of the flora and fauna might respond to the development of a forest type to which they are not adapted and that may not have existed in many areas since Pleistocene glaciation. The dynamic zoning alternatives simulated here do not adequately mimic 'natural' disturbance regimes, and were in fact deterministic with a long temporal period. Furthermore, I simulated a very limited set of silvicultural and management options. However, the dynamic management of disturbance over long time periods allows managers greater flexibility, and coupled with the clustering of disturbance in time and space can be used to sustain larger blocks of mature forest than can a static alternative.

As timber production zones are more tightly clustered in time and space, the effective rotation interval becomes longer, providing large blocks of mature forest habitat on zones nearing the end of rotation. These older forests would be expected to have greater structural complexity than forests managed on a shorter rotation, helping to enhance biodiversity and to maintain soil productivity (Swanson and Franklin, 1992). A greater diversity of seral stages would exist across the landscape, although the interspersion of the types would be less. In addition, stands would be older when they are re-entered, introducing economies of scale in the harvesting and processing of larger trees. However, longer rotations may produce changes in community composition that in some cases may be undesirable. A dynamic zoning strategy allows for flexibility in rotation length (or disturbance interval), while still retaining the benefits of clustered disturbance in time and space.

Clearly, many other factors besides forest fragmentation impact forest management plans. For example, increasing the area of old-growth forest would be difficult on a dynamically zoned land base and would probably require integration of dynamic zoning with old-growth islands (sensu the 'long-rotation island' concept of Harris (1984)). Some flexibility in rotation intervals may be required to meet vegetation management goals on other parts of the landscape. Public acceptance of periodic changes in the location of natural appearing recreation areas is difficult to predict, and may be problematic for the implementation of a dynamic zoning strategy. These issues certainly need to be investigated. Nevertheless, the results of these simulations suggest that it may be technically possible to extract timber from a large land base while maintaining most of that land base in a relatively undisturbed state for long periods of time.

Most eastern forests still bear the legacy of widespread disturbance and abuse, and most are relatively young. It is prudent to protect parts of the forest from timber harvest to develop a diversity of forest conditions across the landscape. However, this may be wise only in the short term, and explicit thought must be given to the nature of disturbance regimes that will be imposed across large forested areas over the long term.

5. Conclusion

It is perhaps inevitable that conflicting demands on our forests will increase. The value of forested ecosystems for recreation and as repositories of biological diversity will increasingly be recognized, while the demand for wood products will also increase. Pressure to provide both commodity and non-commodity values from our forests will require new and creative ways to manage these valuable resources.

A criticism of timber harvest is that it reduces the habitat values of certain species of concern and reduces the aesthetic enjoyment of the forest. A criticism of setting aside lands from timber harvest is that wood fiber is locked up and wasted, putting more pressure on other woodlands and foreign countries to produce the fiber to meet the demands of society. A dynamic zoning paradigm begins to satisfy both these criticisms through better and more judicious integration of multiple uses. When harvests are clustered in both space and time, more forest interior is preserved, and more areas are distant from any signs of recent harvest activity. The specific location of these areas would shift across the landscape on a time scale of several decades, but the amount of land in these conditions would remain constant. If timber harvest activity is moved progressively across the landscape, less of the forest is permanently set aside, and harvested stands will be older on average, introducing economies of scale in their harvest. Even within timber harvest areas, harvesting would be spread out over 30–50 years, so that when stands are cut at the end of the period, the stands cut first will have regenerated to a closed canopy condition. Although a significant portion of a managed forest might still be set aside from timber harvest, a dynamic zoning paradigm could support higher levels of timber extraction with less forest fragmentation than the static zoning alternative. Dynamic zoning also encourages explicit specification of the disturbance regimes that will be imposed across the land base over long time scales.

Acknowledgements

I thank T. Crow, J. Johnson, S. Tang, C. Morgan, S. Shifley, D. Mladenoff and two anonymous reviewers for critical reviews of earlier drafts of the manuscript. I thank L. Burde for editorial assistance.

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